WAVELENGTH CONTROL AND CALIBRATION FOR WAVELENGTH DIVISION MULTIPLEXED OPTICAL COMMUNICATION[*]

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Abstract

Wavelength calibration of equipment in the 1500 nm region is essential to ensure channel stability and characterize optical components for wavelength division multiplexed optical fiber communication systems. We review the wavelength accuracy and stability requirements for these systems and discuss various approaches to meeting these requirements. Our approach is to develop high-accuracy wavelength references for National Institute of Standards and Technology (NIST) internal calibration and moderate-accuracy references as convenient transfer standards to help industry calibrate their instrumentation.

Introduction

Wavelength division multiplexing (WDM) in optical fiber communication systems increases bandwidth by using many wavelength channels. Current WDM systems typically employ 50 or 100 GHz channel spacing (0.4 or 0.8 nm, respectively) in the 1540–1560 nm region, but narrower channel spacing may be implemented soon. Wavelength division multiplexing will likely expand into other wavelength regions as well, possibly covering the entire range from about 1280 to 1630 nm. At the same time, systems are pushing toward higher bit rates, with 10 Gb/s systems currently being introduced and 40 Gb/s systems under development.

Wavelength stability of sources and components and wavelength calibration of equipment are essential for WDM systems. Instruments such as optical spectrum analyzers, tunable lasers, and wavelength meters are used to characterize WDM system components and measure the channel wavelengths. System manufacturers specify that the maximum central frequency deviation of wavelength-selective components should not exceed 20 % of the channel spacing [1]. For a future system with 12.5 GHz channel spacing, this corresponds to a maximum deviation of 2.5 GHz. If WDM systems with narrower channel spacing or widely tunable components are implemented, active frequency stabilization of sources and components may be required. Since the optical bandwidth of a typical signal is large (about 1.2 times the bit rate for an externally modulated non-return-to-zero signal [2]), there is a trade-off between bit rate and channel spacing. A 10 Gb/s signal would not be implemented in a system with a WDM channel spacing narrower than about 12 GHz.

Currently most WDM applications require that equipment be calibrated with an uncertainty in the range of about 0.5 to 5 GHz. However, some applications, particularly in R&D laboratories, require higher accuracy.

Atomic and molecular absorption lines provide wavelength calibration references that are very stable under changing environmental conditions. Molecules such as acetylene and hydrogen cyanide have distinctive absorption features in the 1500 nm region due to rotational-vibrational transitions; these transitions are combination or overtone bands that can be probed directly. Atomic transitions in the 1300–1600 nm region are between excited states and thus require initial excitation by a laser [3] or electric discharge [4]. There is only one gas laser reference line: the 1523 nm helium-neon laser. Other atomic or molecular references can be realized by frequency-doubling 1300–1600 nm light to probe atomic transitions in the 650–800 nm region [5]. Below we describe our research on wavelength calibration references based on atomic and molecular absorption lines.

NIST Wavelength Calibration References

We have developed both moderate accuracy transfer standards and higher accuracy wavelength references for WDM. The transfer standards, which incorporate molecular gas absorption cells, are simple devices to help industry calibrate instrumentation. The higher accuracy references are lasers stabilized to methane and rubidium absorption lines; these references allow us to check the accuracy of our wavelength meter.

1510–1560 nm Transfer Standards

Our moderate accuracy references are NIST Standard Reference Material (SRM) transfer standards based on rotational-vibrational transitions of acetylene, $^{12}C_2H_2$ (SRM 2517a), and hydrogen cyanide, $H^{13}C^{14}N$ (SRM 2519). The $\nu_1 + \nu_3$ combination band of acetylene (Fig. 1) has more than 50 strong absorption lines in the 1510-1540 nm region. The absorption lines of the $2\nu_3$ overtone transition of hydrogen cyanide (Fig. 2) are better placed for current WDM applications, with about 50 lines in the 1530-1565 nm region.
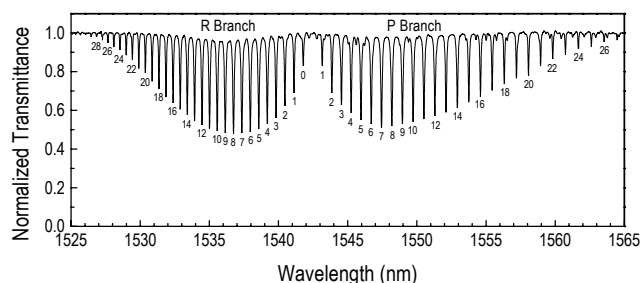
The Standard Reference Materials were designed for calibrating wavelength-measuring instruments such as

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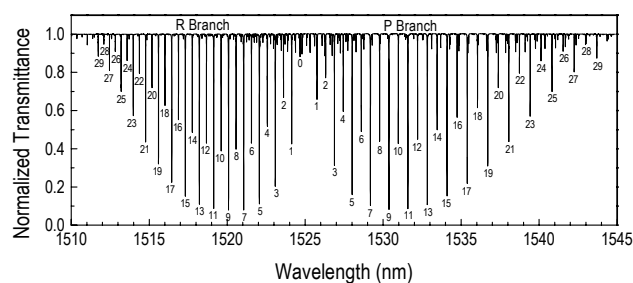
Figure 1 Spectrum of the acetylene $^{12}C_2H_2$ $\nu_1 + \nu_3$ band obtained by scanning a tunable diode laser and measuring the laser power transmitted through a 5 cm long absorption cell filled to a pressure of 6.7 kPa (50 Torr).

Figure 2 Normalized spectrum of the hydrogen cyanide $H^{13}C^{14}N$ $2\nu_3$ band obtained by passing LED light through an SRM unit and recording the spectrum of the transmitted light using an optical spectrum analyzer with 0.1 nm resolution. The HCN gas pressure is 13 kPa (100 Torr) and the optical path length through the gas is 22.5 cm.

optical spectrum analyzers and wavelength meters. The SRM units are optical-fiber-coupled with singlemode fiber, and the spectrum can be observed using a broadband source (such as a light-emitting diode or amplified spontaneous emission source) or a tunable laser. Single-wavelength calibrations using a single line, and scan linearity measurements using multiple lines can be made. NIST has evaluated the uncertainty of the line centers and provides certified wavelength values. Each SRM unit is measured at NIST to assure that it has sufficient gas purity and contains the correct pressure.

The vacuum wavelengths of the acetylene line centers have been measured with a quoted uncertainty of 1.2×10^{-6} nm [6], and the hydrogen cyanide line centers have been measured with a quoted uncertainty of 1.2×10^{-4} nm [7]. Although molecular structure is relatively insensitive to changes in environmental conditions, it is not completely immune, and slight shifts of line centers can occur under certain conditions. The largest potential source of line shift is due to energy level shifts caused by the interaction of the molecules during collisions. This collision-induced line shift (the pressure shift) increases linearly with pressure. The line center values given in Refs. [6] and [7] are for very low pressure conditions and are applicable, at the quoted uncertainty, only to that situation. To provide sufficient signal when used with a 0.1 nm resolution instrument, such

as an optical spectrum analyzer, the gases in the SRMs are at moderate pressures [6.7 kPa (50 Torr) for acetylene, and 13.3 kPa (100 Torr) for hydrogen cyanide]. Since our goal was to certify these SRM references with an uncertainty of less than 1 pm, we measured the pressure shift for both acetylene and hydrogen cyanide.

A schematic diagram of our pressure shift measurement apparatus is shown in Fig. 3. Light from a tunable diode laser is sent through two absorption cells simultaneously, and the transmission through each cell is monitored by detectors. For the acetylene measurement, one cell contains acetylene gas at a relatively low pressure (6.7 kPa) and the other contains either intermediate pressure (29.7 kPa) or high pressure (66 kPa). A third detector monitors the laser power, and a wavelength meter measures the laser's wavelength with an uncertainty of 1 part in 10^7. A computer controls the laser wavelength scan and records the readings of the three detectors and wavelength meter.

Figure 4 shows spectra of line P4 of acetylene $^{12}C_2H_2$, obtained using the low and high pressure cells. The pressure broadening in the high pressure spectrum is obvious. We are primarily interested in the relative shift
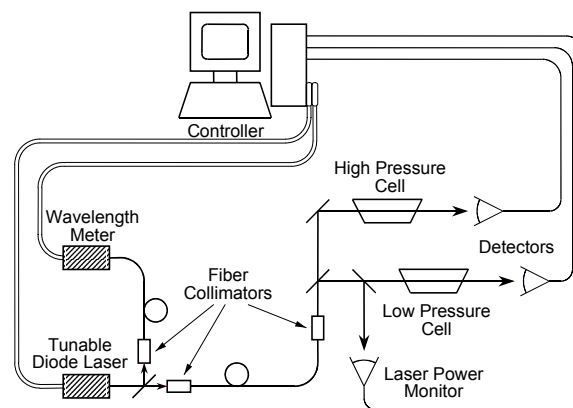
Figure 3 Diagram of pressure shift measurement apparatus.
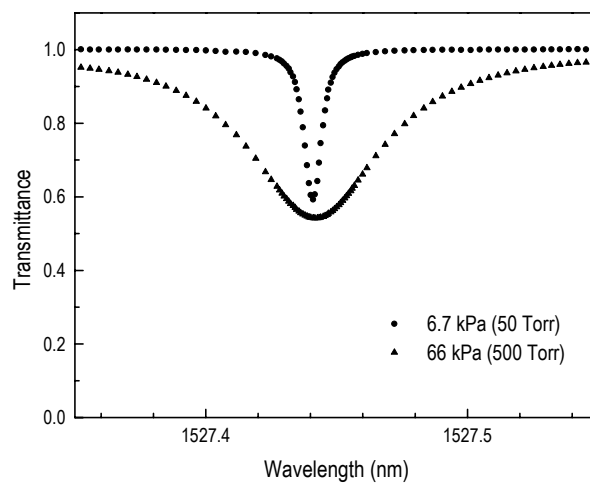
Figure 4 Tunable diode laser scan of $^{12}C_2H_2$ line P4 showing the transmittance through the low and high pressure cells.
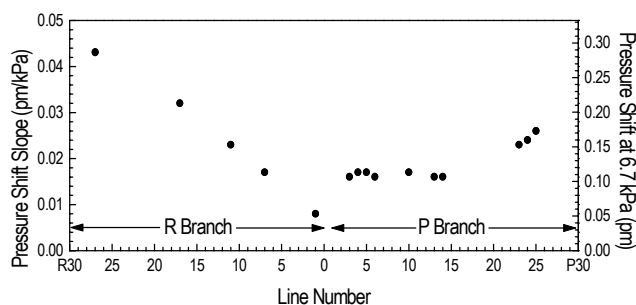
Figure 5 Plot of the pressure shift slope and pressure shift at the SRM pressure of 6.7 kPa (50 Torr) versus line number for the R and P branches of the $^{12}C_2H_2$ $v_1 + v_3$ band.

between the line centers in the low pressure and high pressure cells. Fifteen lines were scanned using these cells and 13 of these lines were also scanned using the low and intermediate pressure cells. Details of our pressure shift measurement and line fitting procedure are given in Ref. [8]. We found that the pressure shift varies with line number, as shown in Fig. 5, but is less than 0.3 pm for the 6.7 kPa (50 Torr) SRM cell pressure. For the acetylene SRM certification, we adjusted the literature line center values for the pressure shift and certify the wavelengths of these 15 lines with an expanded uncertainty (coverage factor $k = 2$, that is, $\pm 2\sigma$) of 0.1 pm. The remainder of the lines in the band are certified with uncertainties ranging from 0.3 to 0.6 pm.

We found that the pressure shift in hydrogen cyanide is more significant (as large as 2 pm for the SRM pressure) and has a larger variation with line number. We have measured the line centers and pressure-induced shifts of 21 hydrogen cyanide lines and certify their wavelengths with an expanded uncertainty of 0.6 pm. The remainder of the lines in the band are certified with an expanded uncertainty of 3 pm, where this uncertainty is dominated by the pressure shift uncertainty [9]. Since the cells containing the gases are sealed, environmental conditions will cause very little change in the line centers. Temperature changes will slightly affect the collision rate (and hence the pressure shift), but this effect is much smaller than the uncertainties quoted above for the certified line centers.

High Accuracy References

To make line center measurements and evaluate the SRM units, we need higher accuracy internal references to check the accuracy of our wavelength meter. We developed a high accuracy reference based on high-resolution spectroscopy of the 780 nm rubidium $5S_{1/2}$ to $5P_{3/2}$ transition using frequency-doubled light. We amplify 1560.5 nm diode laser light using an erbium-doped fiber amplifier and frequency-double it in a periodically poled lithium niobate (PPLN) crystal. We use the resultant 780 nm light to conduct saturated absorption spectroscopy on the rubidium transitions. The hyperfine components of these transitions are less than 10 MHz wide and their absolute frequencies have been measured with an

uncertainty of less than 0.5 MHz [10]. We use these references to calibrate our wavelength meter by stabilizing the frequency-doubled source to several different hyperfine components of the ^{87}Rb transition and comparing our wavelength meter readings to the literature values multiplied by 2. Since the lines are very narrow, the absolute stability of the locked laser is much better than the quoted wavelength meter uncertainty of 1×10^{-7} (about 20 MHz at 1560 nm). From measurements taken before and after our pressure shift scans, we found that the wavelength meter reading was offset by -0.20 ± 0.06 pm ($+25 \pm 8$ MHz). We repeat these measurements periodically to ensure continued accuracy during SRM certification.

The upper section of Fig. 6 shows the methane-stabilized source we constructed as a high accuracy reference in the 1300 nm region. After optical isolation to prevent feedback, the light from a tunable diode laser is split and the smaller portion (15 %) is passed through a gas absorption cell. The transmittance signal is normalized to a reference detector to remove the spectral dependence of the diode laser and isolators. Using frequency modulation and phase-sensitive detection, we stabilize the laser to the center of a methane line.

The larger portion (85 %) of the split laser light is available for the calibration of laboratory equipment. We have performed a beat-note measurement with a laser referenced to the calcium frequency standard developed and maintained by the NIST Time and Frequency Division [11] and have measured a methane transition at 1314 nm with an uncertainty of less than 5 MHz (0.03 pm). This methane-stabilized laser now serves as a NIST internal calibration reference.
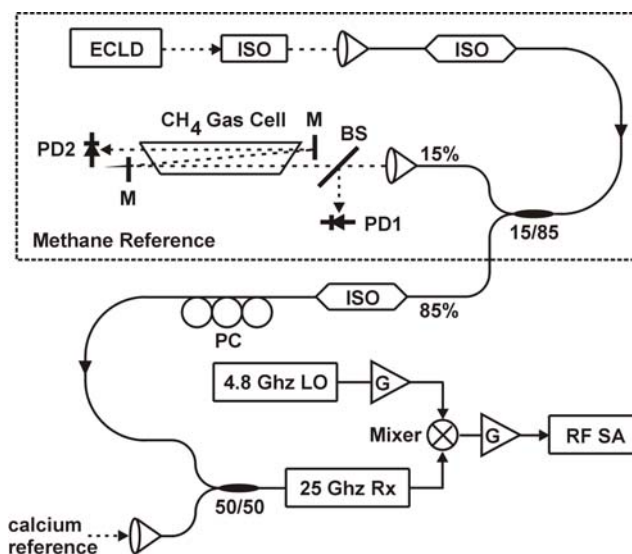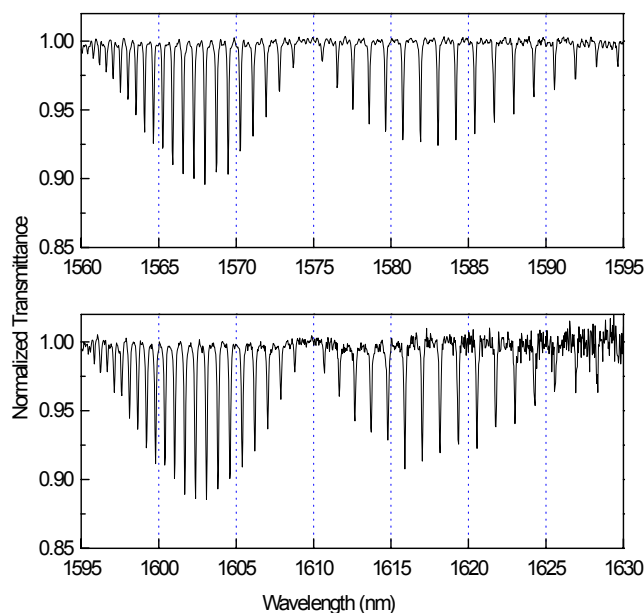

Figure 6 Setup for laser stabilization to methane and beat-note measurement with calcium reference: ECLD, extended cavity laser diode; ISO, isolator; BS, beamsplitter; M, mirror; PD, photodiode; PC, polarization controller; LO, local oscillator; Rx, photoreceiver; SA, spectrum analyzer.
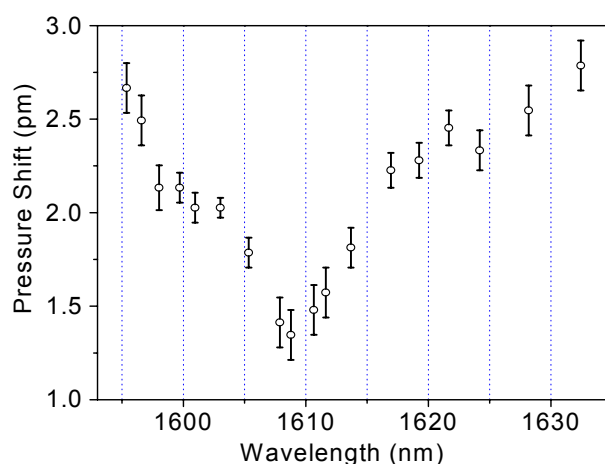
L-band Wavelength References

Wavelength division multiplexing will be implemented in the WDM L-band (approximately 1565–1625 nm) in the near future. We examined a number of molecules as potential references for this region. Hydrogen and deuterium halides generally have strong lines and simple spectra, but of these only hydrogen iodide (HI) [12] has spectral lines in the L-band. Unfortunately, HI has several drawbacks: the spectrum (lines between 1534 and 1595 nm) only partially covers the L-band, some of the lines have significant substructure due to the electric-quadrupole hyperfine interaction, and the gas is difficult to work with due to its reactivity and tendency to decompose. We also investigated various hydrocarbons, halogenated hydrocarbons, and other gases containing one or more CH bonds, since overtones of the CH bond's vibrational energy have spectra near 1550 nm. Although some of the spectra were in the correct location, we found that they were either too weak or highly convoluted, containing hundreds of overlapping lines. These are typically not simple linear molecules, and off-axis vibrations cause complicated spectra.

Carbon monoxide provides suitable wavelength-reference absorption lines in the L-band (see Fig. 7). The carbon 12 isotope ($^{12}C^{16}O$) provides about 40 lines between 1560 and 1595 nm, and $^{13}C^{16}O$ has about 35 lines between 1595 and 1628 nm [13]. These lines are weaker than the absorption lines in either acetylene or hydrogen cyanide, but are not too weak to be considered for a portable

Figure 8 $^{13}C^{16}O$ pressure shift at the SRM pressure of 133 kPa (1000 Torr).

wavelength calibration device. We have built a prototype wavelength SRM device based on carbon monoxide. The unit contains a 20 cm long borosilicate glass cell filled to a pressure of 133 kPa (1000 Torr). Light from a singlemode optical fiber is collimated into a free beam, and then passes through the cell in a four-pass configuration, yielding an 80 cm path length. This provides lines with depths of 5 % to 10 % and widths of 0.04 nm to 0.05 nm, suitable for typical spectrum analyzer or laser calibration. The same packaging is suitable for either $^{12}C^{16}O$ or $^{13}C^{16}O$.

We have measured the pressure shift for both isotopes of carbon monoxide using a procedure similar to that described in Ref. [8]. We measured the line centers and pressure shifts of 14 lines in the $^{12}C^{16}O$ spectrum and 18 lines in the $^{13}C^{16}O$ spectrum (Fig. 8). We also extrapolated the line centers to zero pressure for the lines we measured and compared those values with the literature values. We found that the pressure shift at the SRM pressure of 133 kPa varied between 1 and 3 pm, depending on the line number, and was slightly larger for $^{13}C^{16}O$. Our pressure shift coefficient values for $^{12}C^{16}O$ have a lower uncertainty and agree well with those reported by Picque and Guelachvili [14]. They also agree with the R branch shift coefficients reported by Henningsen, et al. [15] (Henningsen did not report values for the P branch). Our $^{12}C^{16}O$ extrapolated zero-pressure line centers show good agreement, within our uncertainties, with those of Picque, Henningsen, and the HITRAN database [13]. Our shift coefficient and zero-pressure line-center uncertainties are primarily due to background noise in the line scans. Wavelength meter uncertainty also contributes slightly to the zero-pressure line-center uncertainties. There is very little data reported in the literature on the $^{13}C^{16}O$ reference lines. The only line-center values we have found are in the HITRAN database, and we have not located any work on $^{13}C^{16}O$ pressure shift coefficients. Our $^{13}C^{16}O$ zero-pressure line centers show good agreement with the HITRAN data.

Figure 7 Normalized spectrum of the carbon monoxide 3ν transition (upper trace: $^{12}C^{16}O$, lower trace: $^{13}C^{16}O$) obtained by passing LED light through an absorption cell and recording the spectrum of the transmitted light using an optical spectrum analyzer with 0.1 nm resolution. The CO gas pressure is 133 kPa; light makes four passes through the cell for a total optical path length of 80 cm. The noise at longer wavelengths on the lower trace is due to low LED power in that region.

Conclusions

Wavelength calibration of equipment in the near infrared is essential for WDM systems. We have developed convenient transfer standards for wavelength calibration in the 1510–1560 nm region and are developing transfer standards for the 1565–1630 nm region. Wavelength division multiplexing will likely expand into the 1300 and 1400 nm regions, and it will be very difficult to find absolute references for this wide wavelength range. One possibility is the use of calibrated artifact references, such as etalons [16] or fiber Bragg gratings [17]. Artifacts can provide references at arbitrary wavelengths, but they suffer from large sensitivity to changes in temperature, strain, and pressure. Passive or active thermal stabilization can substantially reduce this variability, and the artifacts can be referenced to atomic or molecular standards [16,17].

In order to characterize the transfer standards, we need internal calibration references with higher accuracy (few megahertz) throughout the near IR region. We have established references at 1314 nm and 1560 nm and plan to develop other references in the 1280–1630 nm region in collaboration with the NIST Time and Frequency Division.

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